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Abstract

This paper proposes a group decision-making process by using multi-objective programming to address three-dimensional concurrent engineering (3D-CE) problems involving product, process and supply chain design. This paper uses opinion of decision makers to evaluate of the candidate suppliers and to determine importance of criteria by considering lack knowledge/information in the early design stages. For identifying impact of the lack knowledge/information on selecting the best configuration of product design, assembly/manufacturing process and suppliers of components, a numerical example is represented for two states of intuitionistic fuzzy and fuzzy. The evaluation showed that the configuration selected for two states are completely different.

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Keywords: New product development; Three-Dimensional Concurrent Engineering; Multi-objective programming model; Intuitionistic fuzzy set.

1. Introduction

NPD process is a series of necessary activities for developing a new product that it is including of the growth of its idea, production and introduction into the market. The product design is one of the most important activities in developing new product. A good design process should guarantee both the fulfilment of customer needs and business goals. So, evaluation of product design plays a critical role in the early phase of product development. It can save both cost and time in product development by decreasing the risk of re-design of new product. It is widely accepted that more than 70% of the total product development costs are committed by decisions taken at the early stages of design [1]. The subject is more important when to know that much information about criteria in the early stages of design is not available or is uncertain.

Today, considering of simultaneous different criteria from diverse areas in the early stages of design is inevitable. Fine [2] introduced the term "Three-Dimensional Concurrent Engineering (3D-CE)" that consider, simultaneously, different aspects of the design, process and supply chain in the early stages of the product development.

Selecting of design alternatives is a multi-criteria decision-making process which involves many factors of both customer needs and business constraints. In the early design stages, evaluation of design alternatives is difficult to precisely express by crisp data because the information available is usually imprecise, incomplete or subjective. So, an effective method to evaluate design alternatives in the early stage of design process is inevitable.

In real life, however, the information of an object corresponding to a fuzzy concept may be incomplete; a decision maker (DM) may have a hesitation or uncertainty about the membership degree. Atanassov [3] introduced the concept of intuitionistic fuzzy set (IFS) to deal with this challenge. Expression of hesitation is particularly helpful for decision makers (DMs) when they need to select suppliers in a highly uncertain supply network such as a design product [4]. An IFS-based method can be applied to derive the most appropriate suppliers that its output can be further utilized by a multi-objective optimization model to determine the most appropriate design alternatives.

The paper is organized as follows: section 2 review literature related to 3D-CE. Section 3 describes the basic concepts used in the paper. Section 4 represents the proposed method to choice the best configuration of product design, assembly/manufacturing process and suppliers of components. Section 5 expresses a numerical example to show efficiency of the method. Section 4 represents conclusion and future research.

2. Literature

In the recent years, some papers have argued impact of product design, process and supply chain design on NPD process. Ellram et al. [5] surveyed literature related to mutual fields of 3D-CE (product/process, product/supply chain, and process/supply chain) and done a good review of the 3D-CE. Huang et al. [6] integrated platform product decisions, manufacturing process decisions, and supply sourcing decisions by developing a mathematical model to quantify the relationships among various design decisions. Petersen et al. [7] explained how to integrate suppliers into the new product development process and showed their impacts on process design and supply chain decisions. Fine et al. [8] proposed a goal-programming model to address three-dimensional concurrent engineering (3D-CE) and surveyed relationship between product and supply chain structure. Wang et al. [9] described relation of product characteristics to supply chain strategy and developed an integrated analytic hierarchy process (AHP) and preemptive goal programming (PGP) methodology. Fixon [10] developed a multi-dimensional framework as a coordination mechanism that builds on existing product characteristic such as component commonality, product platforms, and product modularity. Nepal et al. [11] proposed a method based on fuzzy logic to model both product structure and supply chain based on experts` information. Gehin et al. [12] presented a method to support designers in the definition of the product lifecycle scenario, including component lifecycle scenarios, when designing the elements of the structure of the product. Blackhurst et al. [13] used a short network approach to develop the Product Chain Decision Model (PCDM) for considering decisions related to product design and manufacturing process and the impact of such decisions on the supply chain. Ellram and Stanley [14] used the 3D-CE to integrate environmentally responsible manufacturing (ERM) and NPD and surveyed its benefit. Shahrokhi et al. [15] proposed hybrid method by integrating multi-objective programming and fuzzy AHP to address CE problem to select processes and suppliers in an uncertain environment. Shidpour et al. [16] developed a multi-objective linear programming (MOLP) model integrated to TOPSIS method to determine the best configuration product design, assembly process and suppliers by considering qualitative and quantitative criteria in early stages of new product development (NPD) process.

This paper proposes a group decision-making process by using multi-objective programming model to select the best configuration of product design, assembly/manufacturing (A/M) process and suppliers of components. Since in the early design stages much information about criteria is uncertain, we develop a new method based on group decision-making process and intuitionistic fuzzy set. We use opinion of decision makers to construct intuitionistic fuzzy decision matrices by considering lack knowledge/information. These intuitionistic-based decision matrices are used to early evaluate of the candidate supplier and to provide the final set of suppliers as well as to determine importance of criteria. For identifying impact of the lack knowledge / information on selecting the best configuration, a numerical example is represented for two states of intuitionistic fuzzy set and fuzzy set. Results of the evaluation showed that the best configuration for two states is completely different.

3. Background

In this section, we present the basic concepts used in our method.

3.1. Intuitionistic fuzzy sets

Intuitionistic fuzzy sets (IFSs) that are recognized as a generalization of fuzzy set theory is characterized by a membership function and a non-membership function. Let X be a universe of discourse, then a intuitionistic fuzzy set B is defined as:

$$B = \{ \langle x, \mu_B(x), \nu_B(x) \rangle \mid x \in X \} \tag{1}$$

$$0 \le \mu_B(x) + \nu_B(x) \le 1 \quad \forall x \in X \tag{2}$$

where $\mu_B : X \to [0,1]$ and $\nu_B : X \to [0,1]$ are membership and non membership functions, respectively. The hesitation degree is calculated as:

$$\pi_B = 1 - \mu_B(x) - \nu_B(x) \tag{3}$$

If U and V be two intuitionistic fuzzy numbers (IFN), then [3]:

$$U + V = \{ \mu_u(x) + \mu_v(x) - \mu_u(x).\mu_v(x), \upsilon_u(x).\upsilon_v(x) \mid x \in X \} \tag{4}$$

$$\gamma U = \{(1-(1-\mu_u(x))^{\gamma}, \upsilon_u(x)^{\gamma}\},\ \gamma > 0 \tag{5}$$

3.2. Multi-objective linear programming

Zimmermann [17] proposed one method based on fuzzy set theory to solve multi-objective linear programming (MOLP). This method develops membership functions for each objective with considering its upper (L_r^{max}, U_r^{max}) and lower bound (L_r^{min}, U_r^{min}) [13]. They are determined by solving the multi-objective problem, when only one objective is used at each time. Membership function for minimizing objective is obtained as:

$$\mu_{z_r}(x) = \begin{cases} 1 & z_r \le L_r^{min} \\ \dfrac{U_r^{min} - z_r(x)}{U_r^{min} - L_r^{min}} & L_r^{min} \le z_r \le U_r^{min} \\ 0 & z_r \ge U_r^{min} \end{cases} \quad , r = 1, \ldots, n \tag{6}$$

After constructing membership functions, the multi-objective problem converts into a weighted single objective problem as follows:

$$\begin{aligned} & \max \sum_{r=1}^{m} v_r \lambda_r \\ & \lambda (U_r^{min} - L_r^{min}) \le U_r^{min} - z_r(x) \quad , r = 1, \ldots, n \\ & g(x) \le b \\ & \sum_{r=1}^{m} v_r = 1 \\ & x \ge 0,\ \lambda_r \in [0,1] \end{aligned} \tag{7}$$

where v_r is weight of objectives.

4. The proposed method

In this section, we present the method to evaluate design alternatives in the 3D-CE.

Let A= {A_1, …, A_S} be set of supplier alternatives, C= {C_1, C_2, … C_n} be set of criteria, P={p_1,p_2,…,p_y}be set of components, DM={d_1,…,d_k} be set of decision makers (DMs) and w = (w_1, w_2,…, w_n) be weight vector of criteria.

4.1. To determine weight of criteria

The weight values of criteria can be determined by asking all k decision makers to express their opinion on each intuitionistic preference for each pair of criteria as following:

Step1. Calculate degree of membership function (μ_{ij}), the degree of non-membership function (v_{ij}) and hesitation degree (π_{ij}).

Suppose that k_1 DMs express that C_i would be preferred to C_j, k_2 DMs answer that C_i wouldn't be preferred to C_j and k_3 DMs don’t answer due to their lack of knowledge/ indeterminacy about the criteria. So:

$$\mu_{ij} = \sum_{k}^{k_1} w_k \ , v_{ij} = \sum_{k}^{k_2} w_k \ , \pi_{ij} = \sum_{k}^{k_3} w_k \tag{8}$$

and $k_1 + k_2 + k_3 = n$

Step2. Construct an intuitionistic preference relation of criteria

The DMs provides his/her intuitionistic preference for each pair of criteria and constructs an intuitionistic preference relation $X = x_{ij(n\times n)} = (\mu_{ij}, v_{ij}, \pi_{ij})$, $0 \le \mu_{ij} + v_{ij} \le 1$, $\mu_{ji} = v_{ij}$, $v_{ji} = \mu_{ij}$, $\mu_{ii} = v_{ii} = 0.5$ for all $i, j = 1, 2, \ldots, n$ that μ_{ij} , v_{ij} and π_{ij} .

Step3. Use the intuitionistic fuzzy arithmetic averaging operator:

$$x_i = \frac{1}{n} \sum_{j=1}^{n} x_{ij}, \quad i, j = 1, 2, \ldots, n \tag{9}$$

where $x_i = (\mu_i, v_i, \pi_i)$

Step4. Calculate weight of criteria by using following equation:

$$w_i = \frac{(\mu_i + \pi_i (\frac{\mu_i}{\mu_i + v_i}))}{\sum_{i=1}^{n} (\mu_i + \pi_i (\frac{\mu_i}{\mu_i + v_i}))} \tag{10}$$

4.2. Pre-evaluate of all candidate suppliers for different components

Assume that appropriateness of *s* suppliers have to been evaluated on criteria for different components. There, we use a group decision-making method based on IFS to compute weight of objectives, as follows:

Step1. Develop intuitionistic fuzzy decision matrix for each component.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{s1} & r_{s2} & \cdots & r_{sn} \end{bmatrix} \tag{11}$$

where $r_{ij} = (\mu_{ij}, \upsilon_{ij}, \pi_{ij})$ and *i=1,2, ..., s; j=1,2, ..., n.*

For constructing intuitionistic fuzzy decision matrix, from all k decision makers are asked to express their opinion whether each supplier is appropriate or not with respect to each criterion. . Number of answers "Yes", number of answers "No" and number of answers "I do not know, I am not sure, etc." determine values of μ_{ij} ,

ν_{ij} and π_{ij}, respectively in the way was described in the stage 3.1.

Step2. Determine the intuitionistic fuzzy positive-ideal (IFP) and negative-ideal solutions (IFN). Let L1 and L2 be benefit criteria (Larger the better) and cost criteria (smaller the better), respectively. If A^+ be intuitionistic fuzzy positive-ideal solution and A^- be intuitionistic fuzzy negative-ideal solutions, then values of them are obtained as follows:

If $A^+ = (\mu_j^+, \nu_j^+)$ and $A^- = (\mu_j^-, \nu_j^-)$, then:

$$\mu_j^+ = \{(\max_i \mu'_{ij} \mid j \in L_1), (\min_i \mu'_{ij} \mid j \in L_2)\} \tag{12}$$

$$\nu_j^+ = \{(\min_i \upsilon'_{ij} \mid j \in L_1), (\max_i \upsilon'_{ij} \mid j \in L_2)\} \tag{13}$$

$$\mu_j^- = \{(\min_i \mu'_{ij} \mid j \in L_1), (\max_i \mu'_{ij} \mid j \in L_2)\} \tag{14}$$

$$\nu_j^- = \{(\max_i \upsilon'_{ij} \mid j \in L_1), (\min_i \upsilon'_{ij} \mid j \in L_2)\} \tag{15}$$

Step3. Calculate differences between alternatives with A^+ and A^-. In order to measure difference between alternatives on intuitionistic fuzzy set, distance measure proposed by Szmidt and Kacprzyk [18], is used as follows:

$$d(A, A^+) = \sqrt{\frac{1}{2}\left[\sum_{j=1}^{n} w_j[(\mu'_{ij} - \mu_j^+)^2 + (\nu'_{ij} - \nu_j^+)^2 + (\pi'_{ij} - \pi_j^+)^2]\right]} \tag{16}$$

$$d(A, A^-) = \sqrt{\frac{1}{2}\left[\sum_{j=1}^{n} w_j[(\mu'_{ij} - \mu_j^-)^2 + (\nu'_{ij} - \nu_j^-)^2 + (\pi'_{ij} - \pi_j^-)^2]\right]} \tag{17}$$

where w_j is weight of criterion j.

Step4. Calculating the relative distance of each supplier alternative using the following equation:

$$d_i = \frac{d_i^-}{d_i^- + d_i^+} \qquad i = 1, 2, \ldots, s \tag{18}$$

Step5. To select the proper set of suppliers for final evaluation. The suppliers are selected that their values of d_i be equal or more than 0.50.

These stages are repeated for all components that have to provide from suppliers.

4.3. Developing a multi-objective linear programming (MOLP) model

Our proposed approach employs a MOLP model to calculate the best design alternative (version), the appropriate assembly/manufacturing process and the optimum order allocated to the selected suppliers. Notations of the model are defined as follows:

$k=1,2,...,K$	Index of configurations
$i=1,2,...,y$	Index of components
$j=1,2,...,s$	Index of suppliers

Parameters:

D	Anticipated demand for new product
Cap_{ij}	Capacity of supplier j for component *i*
p_{ij}^1	Cost of component *i* purchased from supplier *j*
p_{ki}^2	Assembly cost of component *i* in configuration *k*
t_{ij}^1	Lead time of component *i* purchased from supplier j
t_{ki}^2	Assembly time of component *i* in configuration *k*
q_{ij}	Defect rate of the j^{th} supplier for component i
o_j	Ordering cost to supplier *j*
M	A large number

Decision variables:

x_{ij}	Amount of component *i* Purchased from supplier *j*
u_s	1 if supplier *s* is selected, 0 otherwise
z_k	1 if configuration *k* is selected, 0 otherwise

The objectives and constraints of the model are represented as follow:

$$Min\ y_1 = \sum_{k=1}^{K}\sum_{i=1}^{y}\sum_{j=1}^{s} z_k x_{ij} p_{ij}^1 + \sum_{k=1}^{K}\sum_{i=1}^{y} z_k p_{ki}^2 + \sum_{j=1}^{s} o_j u_j \tag{19}$$

$$Min\ y_2 = \sum_{k=1}^{K}\sum_{i=1}^{y}\sum_{j=1}^{s} \frac{1}{m \times D} z_k x_{ij} t_{ij}^1 + \sum_{k=1}^{K}\sum_{i=1}^{y} z_k t_{ki}^2 \tag{20}$$

$$Min\ y_3 = \sum_{k=1}^{K}\sum_{i=1}^{y}\sum_{j=0}^{s} \frac{1}{m \times D} z_k x_{ij} q_{ij} \tag{21}$$

$$\sum_{j=1}^{S} z_k (x_{ij} - D) = 0 \qquad \forall\ k, i \tag{22}$$

$$z_k x_{ij} \le cap_{ij} \qquad \forall\ i, j, k \tag{23}$$

$$\sum_{k=1}^{K} z_k = 1 \tag{24}$$

$$\sum_{i=1}^{y} z_k x_{ij} \le M u_j \qquad \forall\ j, k \tag{25}$$

$$u_j, z_k \in \{0,1\} \qquad \forall\ j, k \tag{26}$$

$$x_{ij} \ge 0 \qquad \forall\ i, j \tag{27}$$

First objective (19) shows the cost of components purchased from supplier, assembly cost and order cost. The next objective (20) identifies the lead time and assembly time. The third objective (21) represents the average of defect rate. Constraints (22) and (23) show demand and supplier capacity for each component,

Table 1. The information about design alternatives and A&M process

Design alternative	The components	The A&M proposed	A&M cost	A&M time(Min.)
A_1	1,2,3,4,5,<u>6,7</u>	h_1,h_2	U[30,50]	U[2,8]
A_2	1,2,3,4,5,<u>6,8</u>	h_3,h_4,h_5	U[36,60]	U[1,6]
A_3	1,2,3,4,5,<u>7,8</u>	h_6,h_7	U[27,45]	U[2,7]

respectively. Constraint (24) shows that just one configuration is selected. Constraint (25) combines the order cost of several components into one single order for each supplier. Constraints (26) and (27) show binary and continue variables. By solving this MILP model, the order quantity allocated to each supplier is determined.

5. Numerical example

A manufacturer wants to produce a new product to compete with other firms. Experts of production department propose three version of new product. Table 1 shows the alternatives with their possible A/M process and candidate suppliers. Because components 1, 2, 3, 4 and 5 are same in all design alternatives and three components 6, 7, 8 make differences between alternatives, so we evaluate alternatives based on different components. Three criteria cost (C_1), lead time (C_2) and defect rate (C_3) are selected to evaluate design alternatives. The proposed method is applied to determine the best configuration of design product, the A/M process and suppliers as following:

1. To determine weight of criteria described in stage 3.1. In this stage, from 5 DMs is wanted to express their opinion about preference of criteria with asking following question: Do you prefer C_i to C_j?

Dependence to answer of DMs, membership function, non-membership function and hesitation degree are determined. Number of answers "Yes", number of answers "No" and number of answers "I do not know, I am not sure, etc." determine values of μ_{ij} , ν_{ij} and π_{ij} , respectively in the way was described in the stage 3.1. The preference matrix of criteria is shown in Table 2.

2. Pre-evaluate of all candidate suppliers for different components to construct final set of suppliers. This step selects the final set of suppliers among of the six candidate suppliers.

There, we use a group decision-making method based

Table 2. The preference matrix of criteria

	C_1	C_2	C_3	IF	weight
C_1	(0.5,0.5)	(0.65,0.2)	(0.8,0.2)	(0.67,0.27)	0.46
C_2	(0.2,0.65)	(0.5,0.5)	(0.4,0.3)	(0.37,0.46)	0.29
C_3	(0.2,0.8)	(0.3,0.4)	(0.5,0.5)	(0.34,0.55)	0.25

Table 3. The results of steps of 1, 2, 3, 4 and 5 for component 6

P_6	C_1	C_2	C_3	d_i^+	d_i^-	d_i
A_1	(0.45,0.4)	(0.7,0.1)	(0.5,0.2)	0.3	0.37	0.55
A_2	(0.6,0.3)	(0.55,0.25)	(0.35,0.45)	0.2	0.43	0.68
A_3	(0.55,0.35)	(0.5,0.3)	(0.75,0.1)	0.33	0.31	0.48
A_4	(0.75,0.15)	(0.6,0.25)	(0.7,0.2)	0.47	0.19	0.29
A_5	(0.65,0.2)	(0.35,0.45)	(0.8,0.2)	0.33	0.36	0.52
A_6	(0.85,0.15)	(0.45,0.25)	(0.6,0.25)	0.44	0.21	0.32
A^+	(0.45,0.4)	(0.35,0.45)	(0.35,0.45)			
A^-	(0.85,0.15)	(0.7,0.1)	(0.8,0.1)			

on IFS to compute weight of objectives, as follows:

Step1. Develop intuitionistic fuzzy decision matrix for each component

Step2. Determine the IFP and IFN by using equations (12) to (15). In this example all criteria are cost type.

Step3. Calculate differences between alternatives with A^+ and A^- by using equations (16) and (17).

Step4. Calculate the relative distance of each supplier alternative using the equation (18).

Step5. Select the proper set of suppliers for final evaluation. The suppliers are selected that their values of d_i be equal or more than 0.50. Table 3 shows the final set of suppliers for component 6 [A_1, A_2, A_5]. The final set of suppliers for components 7 and 8 are obtained as follows: Component 7: [A_1, A_3, A_5] and Component 8: [A_1, A_2, A_5].

3.3. Using the multi-objective linear programming (MOLP) model of section 4.3 for evaluation of design alternatives. By solving MOLP model, the configuration 1 included design alternative 1, A/M process h_1 and suppliers is determined (Table 4).

For identifying impact of the hesitation -that is obtained from lack of knowledge or indeterminacy about the alternatives- on the results of the proposed method, we evaluate this example again. We assume that DMs have sufficient knowledge or information about accept or reject a decision. So, from all k decision makers are asked to express their opinion about preference of criteria to each other and appropriateness suppliers on criteria. So, Number of answers "Yes" and "No" determine values of μ_{ij} and ν_{ij} , respectively. Thus, The values of $\pi_{ij} = 0$, because DMs have not hesitation about decision. So, the IFS convert to fuzzy set (FS). By

Table 4. The final result for IF evaluation

Component	Supplier	order
6	1,3,5	450, 0,550
7	1,2,5	0,650, 350

Table 5. The final result for fuzzy evaluation

Component	Supplier	order
7	1,3,5	0,650,350
8	1,2,5	700,300, 0

constructing preference matrix to evaluate criteria, weight of criteria is obtained as: w_1=0.44, w_2=0.27, w_3=0.29. By solving MOLP model for this state, the configuration 7 including design alternative 3, assembly/manufacturing process h_7 and suppliers is determined (Table 5).

The Figure 1 compares the orders allocated to suppliers for two states IFS and FS.

Results of two evaluations based on fuzzy and intuitionistic fuzzy shows that lack of knowledge or indeterminacy has direct effects on selecting the best configuration thus whole NPD activities. Because data or information in the early stages of product design is not always available, So, IFS can be used as a tool to consider impact of lack of knowledge.

6. Conclusion

One of the most important activities in developing new product is evaluation of design alternatives in the early design stages. Because of existing imprecise and incomplete information in the early design stages, IFS can be used as a more adaptive tool for expressing uncertainty by defining membership and non-membership functions and hesitation degree.

This paper proposes a new group multi-criteria decision-making method by using IFS and multi-objective linear programming for: a) To determine weight of objectives; b) To determine final set of suppliers from among all candidate suppliers by using a new method based on IFS; c) To determine the best configuration of design alternative, A/M manufacturing process and suppliers by applying MOLP model.

Since in the early stages of product design, we are faced with lack information/ knowledge about design, process and supply chain, so we use from approach intuitionistic fuzzy because of considering hesitation degree. This paper uses opinion a group of DMs to form decision matrix and pairwise comparison matrix based on IFS to determine final set of suppliers and weight of criteria. By applying the method for two states of fuzzy and IF, it is shown that to consider lack of knowledge or indeterminacy by IFS can be impact on evaluation of design alternatives, A/M process and supplier selection and thus all NPD process.

There are a number of opportunities to expand the proposed research. The results obtained from the proposed method can be verified by applying a real case and by considering other criteria- especially qualitative criteria- of product design, supply chain design and assembly/ manufacturing process.

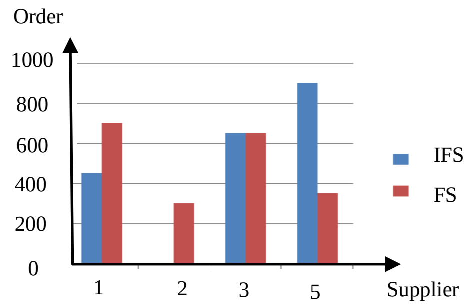

Fig.1. The comparison of orders allocated to suppliers for IFS and FS

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